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Minakuchi et al.

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(45) **Date of Patent: Jan. 10, 2023**

(54) **SUSPENSION CONTROL DEVICE AND SUSPENSION DEVICE**

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(73) Assignee: **HITACHI ASTEMO, LTD.**, Ibaraki (JP)

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Related U.S. Application Data

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(30) **Foreign Application Priority Data**

May 30, 2017 (JP) JP2017-106899

(51) **Int. Cl.**

B60G 17/018 (2006.01)
B60R 16/037 (2006.01)
B60W 10/22 (2006.01)

(52) **U.S. Cl.**

CPC ***B60G 17/0182*** (2013.01); ***B60R 16/037*** (2013.01); ***B60W 10/22*** (2013.01); *B60G 2600/1873* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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Primary Examiner — Aniss Chad
Assistant Examiner — Jennifer M Anda
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(57) **ABSTRACT**

It is an object of the present invention to improve accuracy in estimation of a state of a vehicle in order to achieve excellent ride comfort. An ECU (**600**) includes a reference vehicle model computation section (**1100**), which is configured to calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner.

3 Claims, 8 Drawing Sheets

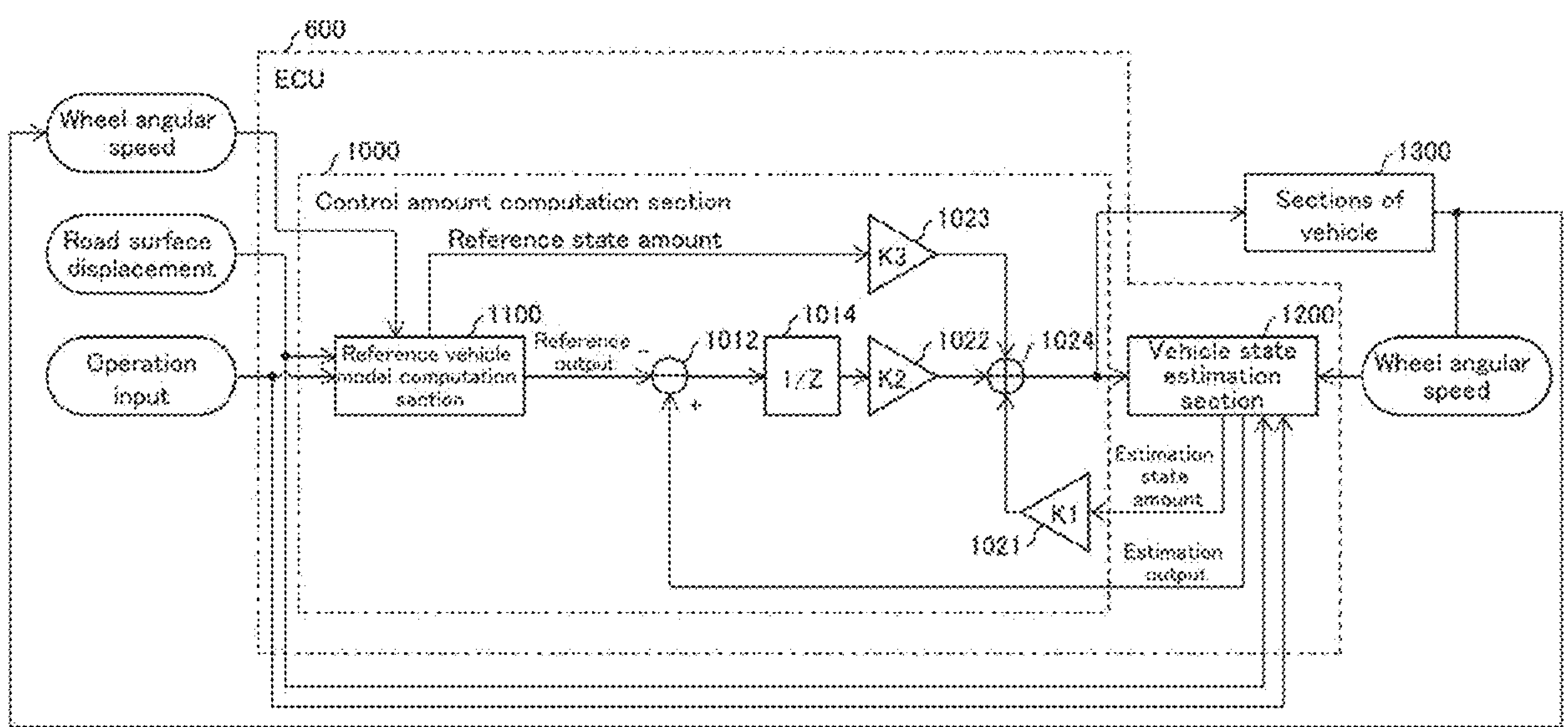

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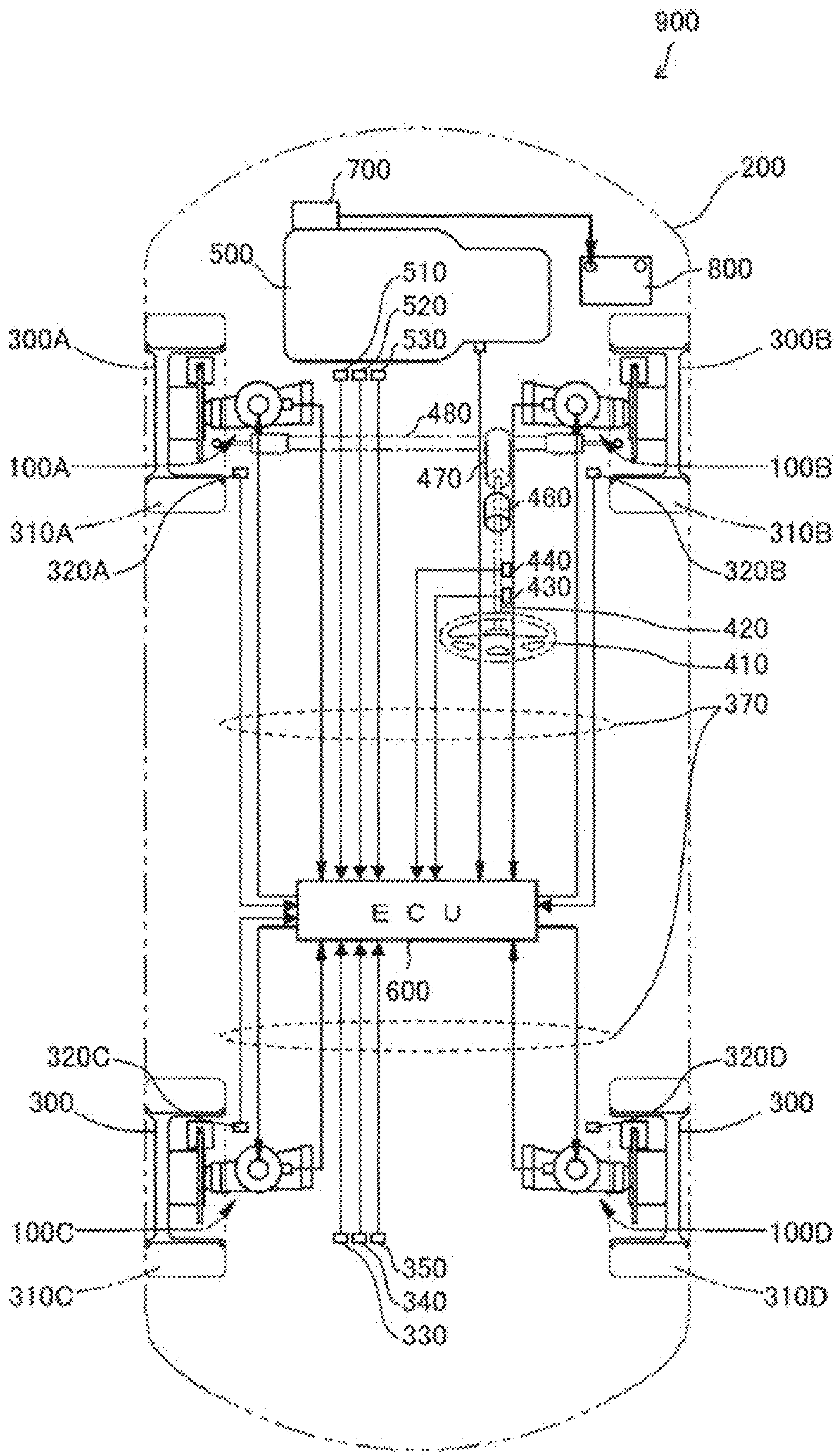
FIG. 1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300B
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100A
100B
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460
310A
310B
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320B
440
430
420
410
370
E C U
600
320C
320D
300
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100C
100D
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340
330
310C
310D

FIG. 2

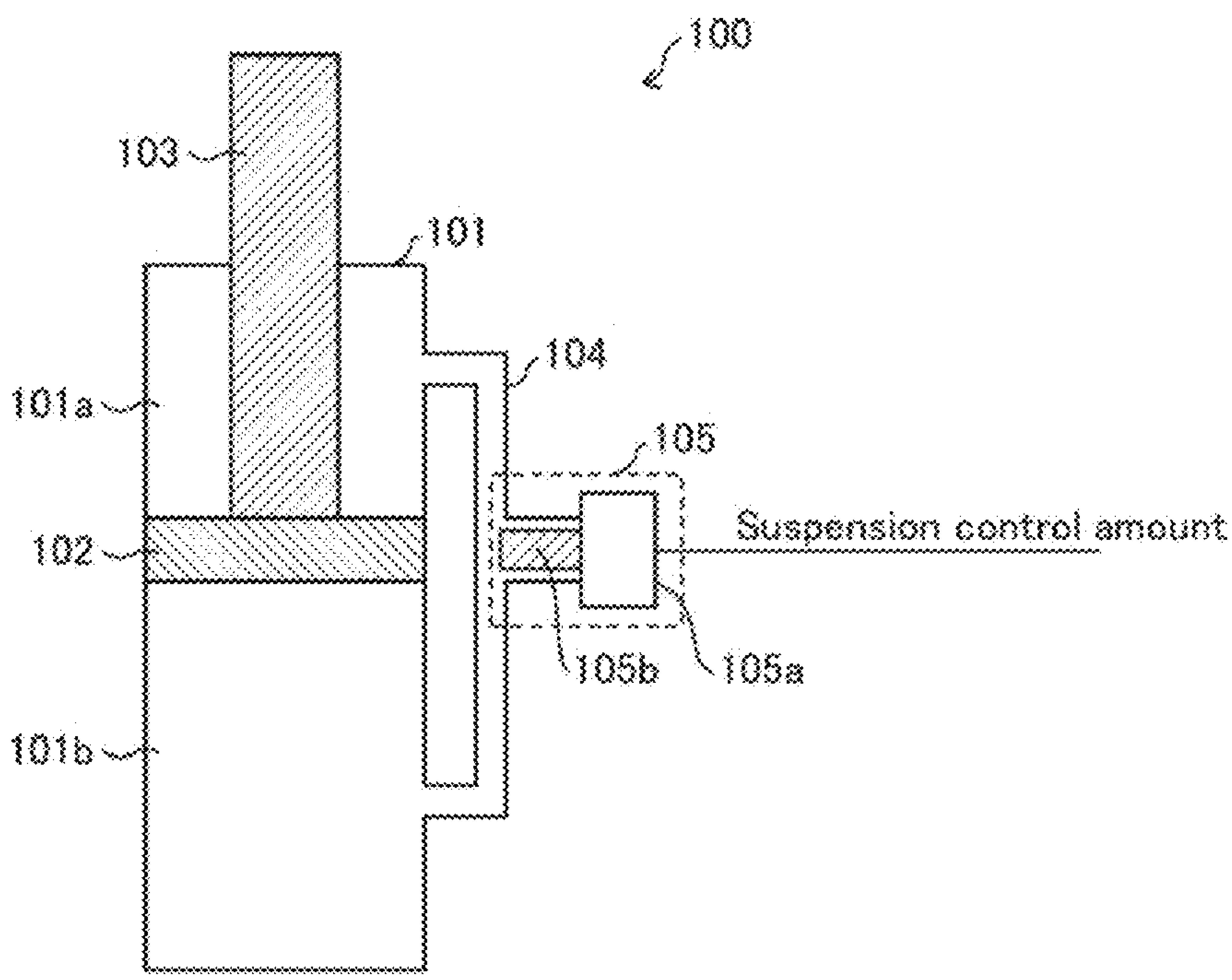

100
103
101
101a
104
105
Suspension control amount
102
105b
105a
101b

FIG. 3

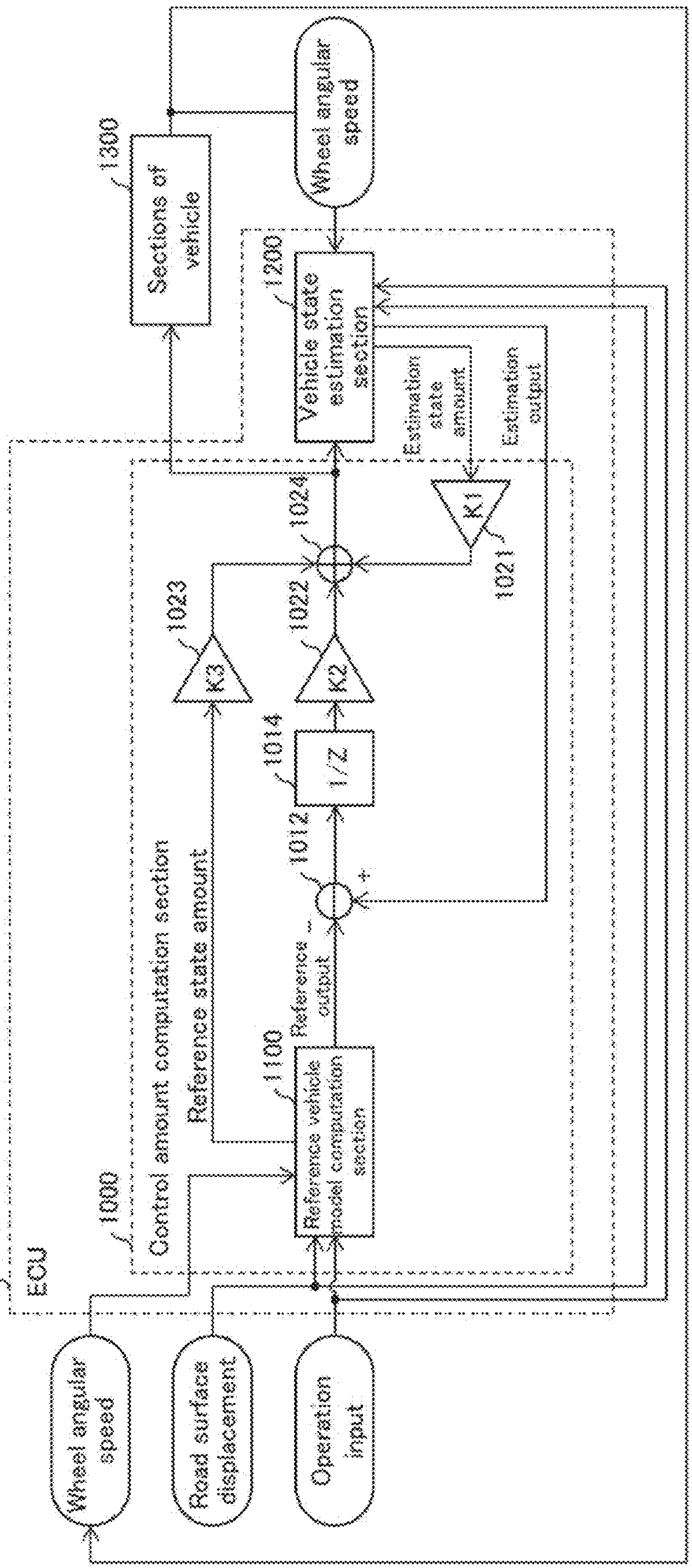
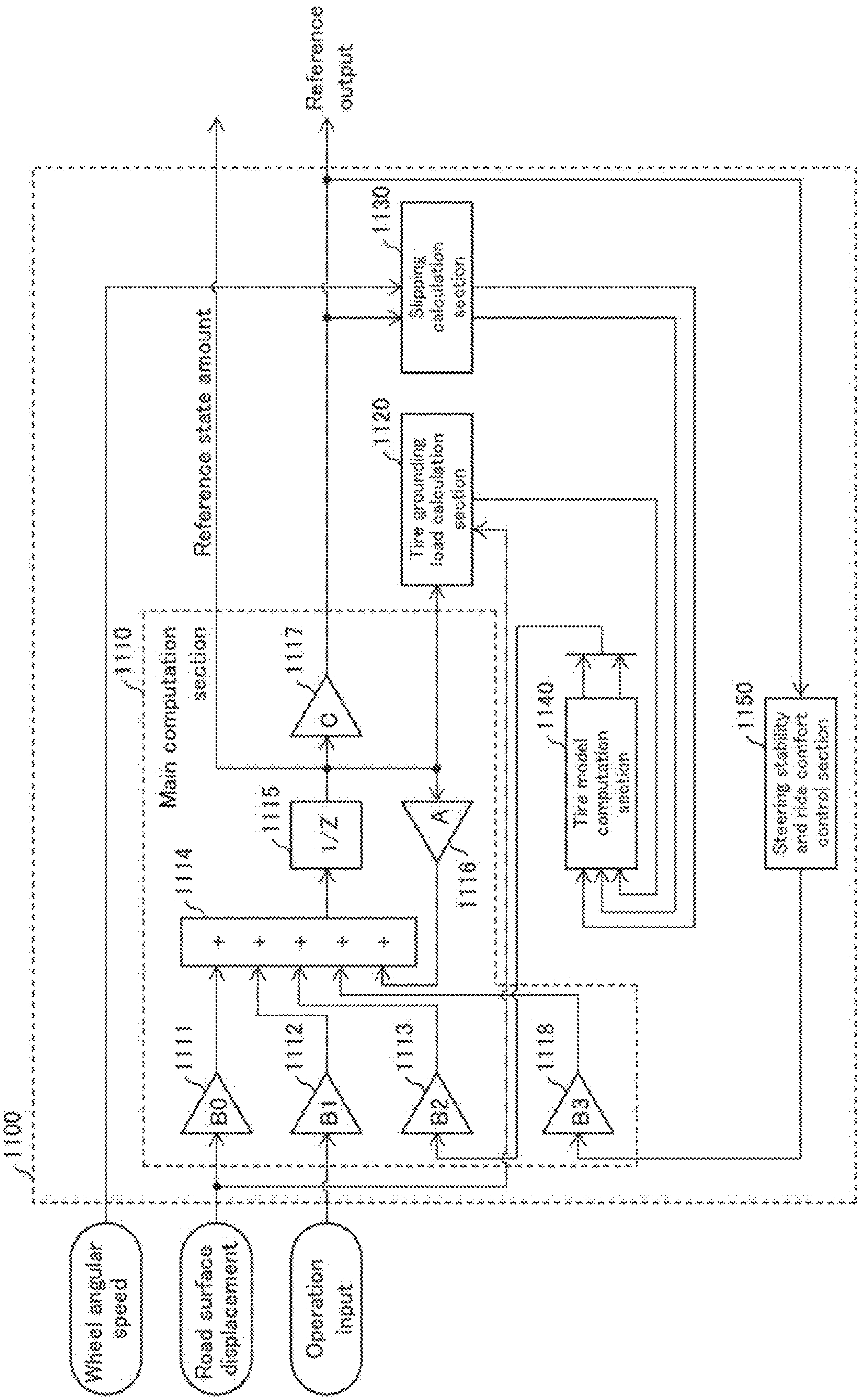

Wheel angular speed
1300
Sections of vehicle
1200
Vehicle state estimation section
Estimation state amount
Estimation output
600
ECU
1000
Control amount computation section
Reference state amount
1100
Reference vehicle model computation section
Reference output
1012
1014
1/Z
1022
K2
1023
K3
1024
1021
K1
Wheel angular speed
Road surface displacement
Operation input

FIG. 4


Reference output
Reference state amount
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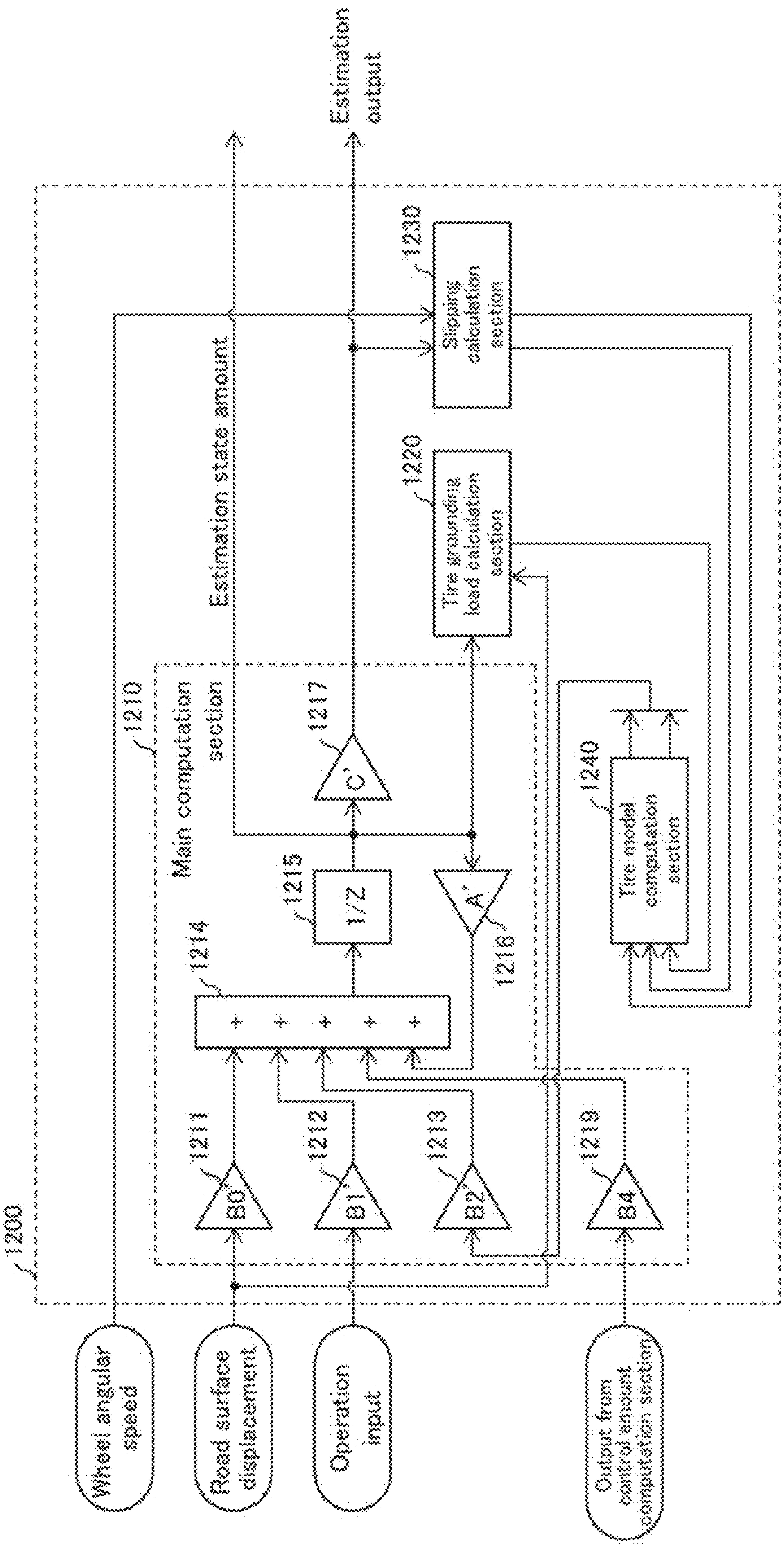
B1
1113
B2
1114
1115
1/Z
1116
A
1117
C
1118
B3
1120
Tire grounding load calculation section
1130
Slippage calculation section
1140
Tire model computation section
1150
Steering stability and ride comfort control section
Wheel angular speed
Road surface displacement
Operation input

FIG. 5

	Planar motion						Upward/downward motion																
	u	v	r	psi	deltaf	deltaVf	w	p	q	phi	theta	DampStfl	DampStfr	DampStrl	DampStrr	z1flm	z1frm	z1rlm	z1rrm	w1flm	w1frm	w1rlm	w1rrm
Planar motion du	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
dv	0.00	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
dr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.14	0.00	0.39	-0.39	0.17	-0.17	0.00	0.00	0.00	0.00	-0.02	0.02	-0.02	0.02
dpsi	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ddeltaf	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ddeltaVf	0.00	0.00	0.00	0.00	-2832.66	-80.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upward/downward motion dw	0.00	0.00	0.00	0.00	0.00	0.00	-7.88	0.00	25.88	0.00	213.33	-40.00	-40.00	-18.00	-18.00	0.00	0.00	0.00	0.00	1.92	1.92	1.92	1.92
dp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-6.10	0.00	5.87	0.00	-56.26	56.26	-24.62	24.62	0.00	0.00	0.00	0.00	2.70	-2.70	2.65	-2.65
dq	0.00	0.00	0.00	0.00	0.00	0.00	-1.25	0.00	-8.63	0.00	38.80	27.08	27.08	-18.05	-18.05	0.00	0.00	0.00	0.00	-1.30	-1.30	1.93	1.93
dphi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
dtheta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
dDampStfl	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.77	-1.04	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00	0.00
dDampStfr	0.00	0.00	0.00	0.00	0.00	0.00	1.00	-0.77	-1.04	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00
dDampStrl	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.75	1.54	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00
dDampStrr	0.00	0.00	0.00	0.00	0.00	0.00	1.00	-0.75	1.54	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
dz1flm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
dz1frm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
dz1rlm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
dz1rrm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
dw1flm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	61.20	-83.20	0.00	-2222.22	1666.67	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00	0.00	0.00
dw1frm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	-61.20	-83.20	0.00	-2222.22	0.00	1666.67	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00	0.00
dw1rlm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	60.00	123.20	0.00	-2222.22	0.00	0.00	750.00	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00
dw1rrm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	-60.00	123.20	0.00	-2222.22	0.00	0.00	0.00	750.00	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00

FIG. 6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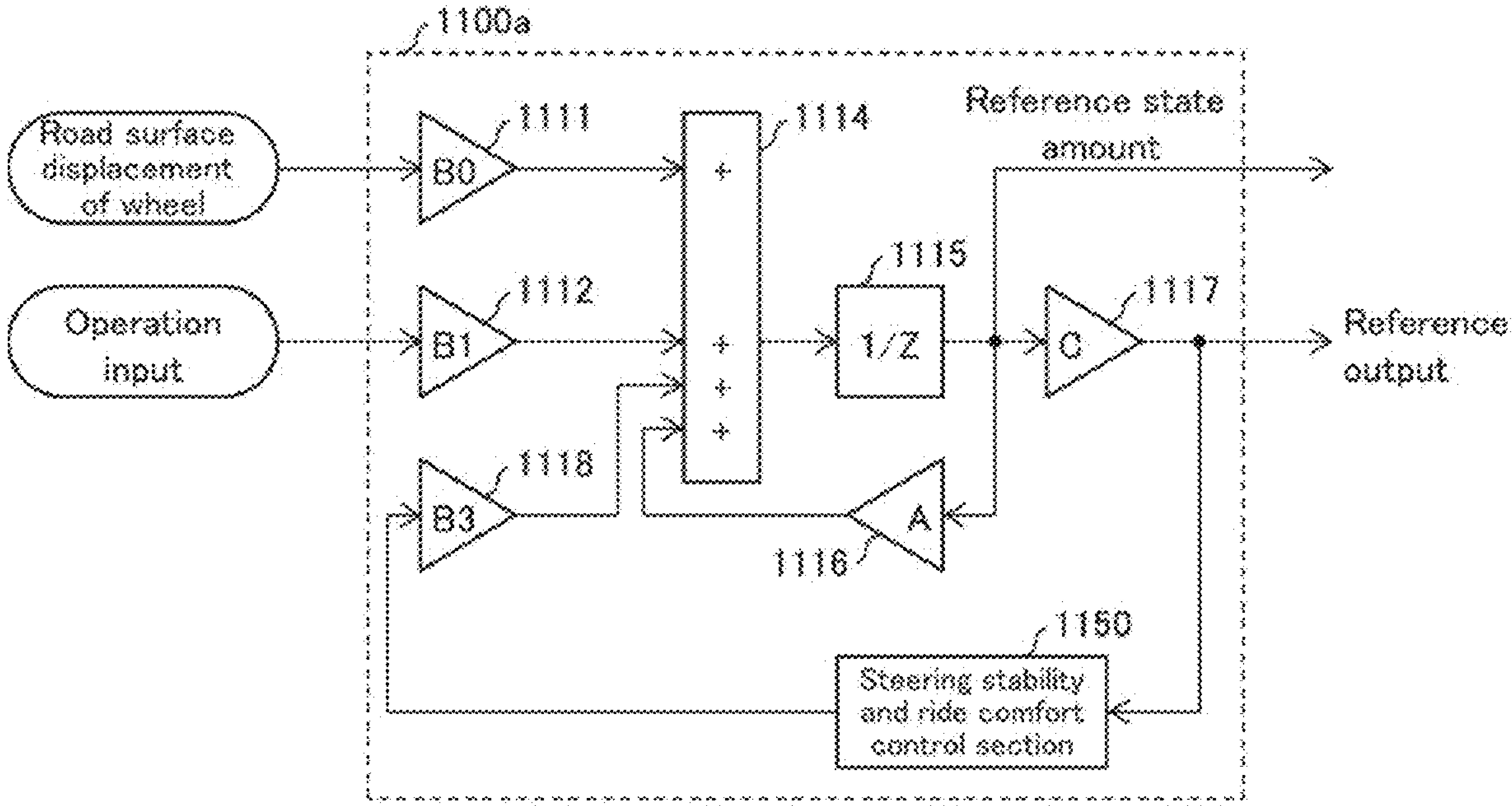
B2'
1214
1215
1/Z
1216
A'
1217
C'
1219
B4
1220
Tire grounding load calculation section
1230
Sloping calculation section
1240
Tire model computation section
Wheel angular speed
Road surface displacement
Operation input
Output from control amount computation section

FIG. 7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Road surface displacement of wheel
Operation input
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1111
B1
1112
B3
1118
1114
+
+
+
+
1115
1/Z
1117
C
A
1116
Reference state amount
Reference output
1150
Steering stability and ride comfort control section

FIG. 8

		Planar motion						Upward/downward motion																
		u	v	r	psi	deltaf	deltaVf	w	p	q	phi	theta	DampStfl	DampStfr	DampStrl	DampStrr	z1flm	z1frm	z1rlm	z1rrm	w1flm	w1frm	w1rlm	w1rrm
Planar motion	du	-7.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.83	0.00	-0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	dv	0.00	-4.73	-25.82	0.00	58.39	0.00	0.00	-2.27	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	dr	0.00	0.36	-6.95	0.00	32.55	0.00	0.00	0.52	0.00	0.14	0.00	0.39	-0.39	0.17	-0.17	0.00	0.00	0.00	0.00	-0.02	0.02	-0.02	0.02
	dpsi	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ddeltaf	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ddeltaVf	0.00	0.00	0.00	0.00	-2832.68	-80.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upward/downward motion	dw	0.00	0.00	0.00	0.00	0.00	0.00	-7.88	0.00	25.88	0.00	213.33	-40.00	-40.00	-16.00	-16.00	0.00	0.00	0.00	0.00	1.92	1.92	1.92	1.92
	dp	0.00	-4.47	1.93	0.00	53.38	0.00	0.00	-10.25	0.00	5.87	0.00	-56.26	56.26	-24.82	24.82	0.00	0.00	0.00	0.00	2.70	-2.70	2.65	-2.65
	dq	2.66	0.00	0.00	0.00	0.00	0.00	-1.25	0.00	-9.91	0.00	38.80	27.08	27.08	-18.05	-18.05	0.00	0.00	0.00	0.00	-1.30	-1.30	1.93	1.93
	dphi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	dtheta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	dDampStfl	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.77	-1.94	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00	0.00
	dDampStfr	0.00	0.00	0.00	0.00	0.00	0.00	1.00	-0.77	-1.94	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00
	dDampStrl	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.75	1.54	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00
	dDampStrr	0.00	0.00	0.00	0.00	0.00	0.00	1.00	-0.75	1.54	0.00	-27.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
	dz1flm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
	dz1frm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
	dz1rlm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
	dz1rrm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	dw1flm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	61.20	-83.20	0.00	-2222.22	1666.67	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00	0.00	0.00
	dw1frm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	-61.20	-83.20	0.00	-2222.22	0.00	1666.67	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00	0.00
	dw1rlm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	60.00	123.20	0.00	-2222.22	0.00	0.00	750.00	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00	0.00
	dw1rrm	0.00	0.00	0.00	0.00	0.00	0.00	30.00	-60.00	123.20	0.00	-2222.22	0.00	0.00	0.00	750.00	0.00	0.00	0.00	-8333.33	0.00	0.00	0.00	-80.00

SUSPENSION CONTROL DEVICE AND SUSPENSION DEVICE

This application is a Continuation of PCT International Application No. PCT/JP2017/022733 filed in Japan on Jun. 20, 2017, which claims the benefit of Patent Application No. 2017-106899 filed in Japan on May 30, 2017, the entire contents of which are hereby incorporated by reference.

TECHNICAL FIELD

The present invention relates to a suspension control device and a suspension device each of which controls a suspension to follow a reference vehicle model.

BACKGROUND ART

There has been known a technology for improving ride comfort of a vehicle by estimating a state of the vehicle and controlling the vehicle on the basis of the state estimated. This technology uses (i) a reference vehicle model for calculating a target value in vehicle control and (ii) an estimation vehicle model for estimating a state of the vehicle.

For example, Patent Literature 1 discloses a technology in which a control amount by which a vehicle adjustment member is controlled is determined on the basis of an optimum feedback gain that has been preset in accordance with a dynamic model related to a height of a vehicle.

Further, Patent Literature 2 discloses a technology of obtaining an estimated yaw rate and a reference yaw rate on the basis of a model of a vehicle and controlling a steering characteristic on the basis of these yaw rates.

CITATION LIST

Patent Literature

Patent Literature 1

Japanese Patent Application Publication, Tokukaisho, No. 61-178212 (Publication Date: Aug. 9, 1986)

Patent Literature 2

Japanese Patent Application Publication, Tokukai, No. 2004-189117 (Publication Date: Jul. 8, 2004)

SUMMARY OF INVENTION

Technical Problem

In order to achieve excellent ride comfort, it is preferable to suitably express a behavior of the vehicle with use of a reference vehicle model.

It is an object of the present invention to provide a suspension control device and a suspension device each of which uses a reference vehicle model and can suitably express a behavior of a vehicle.

Solution to Problem

In order to attain the object, a suspension control device in accordance with the present invention is a suspension control device configured to control a suspension to follow a reference vehicle model, including a reference vehicle model computation section configured to carry out computation with use of the reference vehicle model, the reference vehicle model computation section configured to calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner.

Further, a suspension device in accordance with the present invention is a suspension device, including: a suspension; and a suspension control section configured to control the suspension to follow a reference vehicle model, the suspension control section including a reference vehicle model computation section configured to carry out computation with use of the reference vehicle model, the reference vehicle model computation section configured to calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner.

Advantageous Effects of Invention

According to a suspension control device in accordance with the present invention, it is possible to suitably express a behavior of a vehicle. This makes it possible to achieve excellent ride comfort.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a view schematically illustrating a configuration of a vehicle in accordance with Embodiment 1 of the present invention.

FIG. **2** is a cross-sectional view schematically illustrating an example of a configuration of a hydraulic shock absorber of a suspension in accordance with Embodiment 1 of the present invention.

FIG. **3** is a block diagram schematically illustrating a configuration of an ECU in accordance with Embodiment 1 of the present invention.

FIG. **4** is a block diagram illustrating an example of a configuration of a reference vehicle model computation section in accordance with Embodiment 1 of the present invention.

FIG. **5** is a table illustrating a specific example of components of a system matrix which is used in computation carried out by a reference vehicle model computation section in accordance with Embodiment 1 of the present invention.

FIG. **6** is a block diagram illustrating an example of a configuration of a vehicle state estimation section in accordance with Embodiment 1 of the present invention.

FIG. **7** is a block diagram illustrating an example of a configuration of a reference vehicle model computation section in accordance with Embodiment 2 of the present invention.

FIG. **8** is a table illustrating an example of details of components of a system matrix which is used in computation carried out by the reference vehicle model computation section in accordance with Embodiment 2 of the present invention.

DESCRIPTION OF EMBODIMENTS

Embodiment 1

The following description will discuss Embodiment 1 of the present invention in detail.

Configuration of Vehicle **900**

FIG. **1** is a view schematically illustrating a configuration of a vehicle **900** in accordance with Embodiment 1. As illustrated in FIG. **1**, the vehicle **900** includes suspensions

100, a vehicle body 200, wheels 300, tires 310, a steering member 410, a steering shaft 420, a torque sensor 430, a rudder angle sensor 440, a torque application section 460, a rack-and-pinion mechanism 470, a rack axis 480, an engine 500, an ECU (Electronic Control Unit) (steering control device, suspension control device, suspension control section) 600, a power generator 700, and a battery 800. Note that the suspensions 100 and the ECU 600 constitute a suspension device in accordance with Embodiment 1.

The wheels 300, to which the tires 310 are mounted, are suspended from the vehicle body 200 with use of the suspensions 100. The vehicle 900 is a four-wheel vehicle, and includes four suspensions 100, four wheels 300, and four tires 310, accordingly.

Note that a tire and a wheel for a left front wheel, a right front wheel, a left rear wheel, and a right rear wheel may be referred to respectively as a tire 310A and a wheel 300A, a tire 310B and a wheel 300B, a tire 310C and a wheel 300C, and a tire 310D and a wheel 300D. Likewise, a configuration associated with the left front wheel, the right front wheel, the left rear wheel, and the right rear wheel may hereinafter be represented with use of reference signs "A," "B," "C," and "D," respectively.

The suspensions 100 each include a hydraulic shock absorber, an upper arm, and a lower arm. The hydraulic shock absorber, for example, includes a solenoid valve which is an electromagnetic valve that adjusts a damping force generated by the hydraulic shock absorber. Note, however, that Embodiment 1 is not limited to this. The hydraulic shock absorber may employ, as the electromagnetic valve that adjusts a damping force, an electromagnetic valve other than a solenoid valve. For example, the hydraulic shock absorber may include, as the electromagnetic valve, an electromagnetic valve that utilizes a magnetohydrodynamic flow (a magnetic fluid).

The power generator 700 is annexed to the engine 500, and electricity generated by the power generator 700 is accumulated in the battery 800.

The steering member 410, which is operated by a driver, is connected to one end of the steering shaft 420 so that the steering member 410 can transmit a torque to the one end. The other end of the steering shaft 420 is connected to the rack-and-pinion mechanism 470.

The rack-and-pinion mechanism 470 is a mechanism for converting a rotation about an axis of the steering shaft 420 into a displacement of the rack axis 480 along an axial direction of the rack axis 480. In a case where the rack axis 480 is displaced along the axial direction, the wheel 300A and the wheel 300B are steered, each via a tie rod and a knuckle arm.

The torque sensor 430 detects a steering torque applied to the steering shaft 420, i.e., a steering torque applied to the steering member 410, and provides, to the ECU 600, a torque sensor signal indicative of a result thus detected. More specifically, the torque sensor 430 detects of a twist of a torsion bar provided inside the steering shaft 420 and outputs a result thus detected as the torque sensor signal. Note that the torque sensor 430 may be a magnetostrictive torque sensor.

The rudder angle sensor 440 detects a rudder angle of the steering member 410 and provides a result thus detected to the ECU 600.

The torque application section 460 applies, to the steering shaft 420, an assist torque or a reaction torque in accordance with a steering control amount supplied from the ECU 600. The torque application section 460 includes (i) a motor that generates the assist torque or the reaction torque in accordance with the steering control amount and (ii) a torque transmission mechanism that transmits the torque generated by the motor to the steering shaft 420.

Note that specific examples of "control amount" herein encompass electric current value, duty ratio, damping factor, damping ratio, and the like.

Note that in the above description, the expression "connected so that . . . can transmit a torque" means that one member is connected to the other member so that a rotation of the one member causes a rotation of the other member. For example, the expression encompass at least (i) a case in which one member and the other member are integrally molded, (ii) a case in which one member is directly or indirectly fixed to the other member, and (iii) a case in which one member and the other member are connected to each other so that the one member and the other member move in conjunction with each other via a joint member or the like.

Further, although the above example of a steering device has a configuration in which the members from the steering member 410 through the rack axis 480 are always mechanically connected to one another, Embodiment 1 is not limited to this. The steering device in accordance with Embodiment 1 may be a steer-by-wire type steering device, for example. The following description in the present specification is also applicable to the steer-by-wire type steering device.

The ECU 600 centrally controls various electronic devices included in the vehicle 900. More specifically, the ECU 600 adjusts a steering control amount to be supplied to the torque application section 460, thereby controlling an intensity of an assist torque or a reaction torque to be applied to the steering shaft 420.

Further, the ECU 600 controls the suspensions 100 by supplying a suspension control amount. More specifically, the ECU 600 supplies, to the solenoid valve of the hydraulic shock absorber included in each of the suspensions 100, a suspension control amount so as to control the solenoid valve to open and close. To enable this control, an electric power line is provided for supplying, from the ECU 600 to the solenoid valve electricity, electricity for driving the solenoid valve.

Further, the vehicle 900 includes (i) wheel speed sensors 320 that are provided for the respective wheels 300 and each detect a wheel speed of a corresponding one of the wheels 300 (an angular speed of the corresponding one of the wheels), (ii) a lateral G sensor 330 that detects an acceleration in a lateral direction of the vehicle 900, (iii) a front and rear G sensor 340 that detects an acceleration in a front and rear direction of the vehicle 900, (iv) a yaw rate sensor 350 that detects a yaw rate of the vehicle 900, (v) an engine torque sensor 510 that detects a torque generated by the engine 500, (vi) an engine RPM sensor 520 that detects an RPM of the engine 500, and (vii) a brake pressure sensor 530 that detects a pressure applied to a brake fluid that a braking device has. Results detected by these various sensors are supplied to the ECU 600.

Although not illustrated, the vehicle 900 includes the braking device, which can be controlled by (i) an antilock brake system (ABS) that is a system for preventing wheels from locking up during braking, (ii) a traction control system (TCS) for preventing wheels from spinning out during acceleration or the like, and (iii) a vehicle stability assist (VSA) which is a control system for stabilizing vehicle behaviors and is capable of yaw moment control during turning, automatic braking for a brake assist function, and the like.

Note that the ABS, the TCS, and the VSA (i) compare a wheel speed, which is determined in accordance with an estimated car body speed, with a wheel speed, which is detected by each wheel speed sensor **320** and (ii) in a case where the values of these two wheel speeds differ by a predetermined value or more, determine that the wheel is slipping. Through this process, the ABS, the TCS, and the VSA carry out an optimum brake control and/or an optimum traction control in accordance with a driving state of the vehicle **900**, so as to contribute to the stabilization of behaviors of the vehicle **900**.

Supply of results detected by the above-described various sensors and transmission of a control signal from the ECU **600** to sections are carried out via a controller area network (CAN) **370**.

Suspensions **100**

FIG. **2** is a cross-sectional view schematically illustrating an example of a configuration of a hydraulic shock absorber of each suspension **100** in accordance with Embodiment 1. As illustrated in FIG. **2**, the suspension **100** includes a cylinder **101**, a piston **102** slidably provided inside the cylinder **101**, and a piston rod **103** fixed to the piston **102**. The cylinder **101** is partitioned by the piston **102** into an upper chamber **101***a* and a lower chamber **101***b*. The upper chamber **101***a* and the lower chamber **101***b* are filled with a hydraulic fluid.

As illustrated in FIG. **2**, the suspension **100** includes a communication passage **104** which allows the upper chamber **101***a* and the lower chamber **101***b* to communicate with each other, and a solenoid valve **105** which adjusts a damping force of the suspension **100** is provided on the communication passage **104**.

The solenoid valve **105** includes a solenoid **105***a* and a valve **105***b* which is driven by the solenoid **105***a* so as to change a cross-sectional area of a flow channel of the communication passage **104**.

The solenoid **105***a* inserts and retracts the valve **105***b* in accordance with a suspension control amount supplied from the ECU **600**. This causes a change in the cross-sectional area of the flow channel of the communication passage **104** and causes a change in the damping force of the suspension **100**, accordingly.

Note that the suspension **100** may be an active suspension or an air suspension.

ECU **600**

The following description will discuss details of the ECU **600** with reference to other drawings. FIG. **3** is a view schematically illustrating a configuration of the ECU **600**.

As illustrated in FIG. **3**, the ECU **600** includes a control amount computation section **1000** and a vehicle state estimation section **1200**. The ECU **600** controls sections **1300** of the vehicle to follow a reference vehicle model (described later). The sections **1300** of the vehicle illustrated in FIG. **4** represent (i) sections of the vehicle **900** that are controlled with reference to a result of computation carried out by the control amount computation section **1000** and (ii) various sensors for obtaining a state amount of the vehicle **900**. Examples of the sections to be controlled of the vehicle **900** encompass the suspensions **100** and the torque application section **460**, and examples of the various sensors encompass the yaw rate sensor **350**.

Control Amount Computation Section

As illustrated in FIG. **3**, the control amount computation section **1000** includes a reference vehicle model computation section **1100**, a subtractor **1012**, an integrator **1014**, a first amplifier **1021**, a second amplifier **1022**, a third amplifier **1023**, and an adder **1024**.

The reference vehicle model computation section **1100** carries out computation with respect to an input value with use of a vehicle model for reference and supplies a reference output, which is a result of the computation, to the subtractor **1012**. Further, the reference vehicle model computation section **1100** supplies various state amounts that are subjects of the computation to the third amplifier **1023**, each as reference state amounts. The reference output outputted from the reference vehicle model computation section **1100** serves as a target value in vehicle control. Note that the reference output constitutes at least part of the various state amounts that are subjects of the computation.

Examples of an input to the reference vehicle model computation section **1100** encompass a road surface displacement and an operation input, as illustrated in FIG. **3**. Note that the operation input includes a steering angle of the steering member **410**.

Examples of the reference state amount supplied from the reference vehicle model computation section **1100** to the subtractor **1012** and the third amplifier **1023** encompass at least one of sprung vertical speed (i.e., vertical speed of a sprung portion) w of the vehicle body **200**, roll rate p of the vehicle body **200**, pitch rate q of the vehicle body **200**, and yaw rate r of the vehicle body **200**. Note that a more specific configuration of the reference vehicle model computation section **1100** will be described later.

The subtractor **1012** obtains an estimation output from the vehicle state estimation section **1200** (described later), subtracts, from the estimation output thus obtained, the reference output outputted from the reference vehicle model computation section **1100**, and supplies a result of subtraction thus carried out to the integrator **1014**.

Examples of the estimation output and an estimation state amount, which are supplied from the vehicle state estimation section **1200** to the subtractor **1012** and the first amplifier **1021**, respectively, encompass an estimated value of sprung vertical speed, an estimated value of roll rate, and an estimated value of pitch rate of the vehicle body **200**, and the like.

The integrator **1014** integrates the result of the subtraction carried out by the subtractor **1012**. A result of integration thus carried out is supplied to the second amplifier **1022**.

The first amplifier **1021** amplifies, with use of an amplification coefficient K**1**, the estimation state amount supplied from the vehicle state estimation section **1200** and supplies a result of amplification thus carried out to the adder **1024**.

The second amplifier **1022** amplifies, with use of an amplification coefficient K**2**, the result of the integration carried out by the integrator **1014** and supplies a result of amplification thus carried out to the adder **1024**.

The third amplifier **1023** integrates, with use of an amplification coefficient K**3**, the reference state amount supplied from the reference vehicle model computation section **1100** and supplies a result of integration thus carried out to the adder **1024**.

The adder **1024** adds the result of the amplification carried out by the first amplifier **1021**, the result of the amplification carried out by the second amplifier **1022**, and the result of the amplification carried out by the third amplifier **1023**, and supplies a result of addition thus carried out to the vehicle state estimation section **1200** and the sections **1300** of the vehicle. The result of the addition carried out by the adder **1024** represents a result of computation carried out by the control amount computation section **1000**.

Since the control amount computation section **1000** includes (i) the subtractor **1012** that subtracts the reference output, which is an output value outputted from the reference vehicle model computation section **1100**, from the estimation output, which is an output value outputted from the vehicle state estimation section **1200**, (ii) the integrator **1014** that integrates the result of the subtraction carried out by the subtractor **1012**, (iii) the first amplifier **1021** that amplifies the estimation state amount, which is a subject of computation carried out by the vehicle state estimation device **1200**, (iv) the second amplifier **1022** that amplifies the result of the integration carried out by the integrator **1014**, (v) the third amplifier **1023** that amplifies the reference state amount, which is a subject of computation carried out by the reference vehicle model computation section **1100**, and (vi) the adder **1024** that adds the result of the amplification carried out by the first amplifier **1021**, the result of the amplification carried out by the second amplifier **1022**, and the result of the amplification carried out by the third amplifier **1023**, it is possible to follow a reference model characteristic without deviation.

Further, since the control amount computation section **1000** includes the integrator **1014**, it is possible to follow the reference model characteristic without deviation.

Reference Vehicle Model Computation Section

The following description will discuss in detail a configuration of the reference vehicle model computation section **1100** with reference to FIG. **4**. FIG. **4** is a block diagram illustrating a configuration of the reference vehicle model computation section **1100**. As illustrated in FIG. **4**, the reference vehicle model computation section **1100** includes a main computation section **1110**, a tire grounding load calculation section **1120**, a slipping calculation section **1130**, and a tire model computation section **1140**.

Main Computation Section

The main computation section **1110** refers to one or more input values and carries out linear computation for a state amount related to a state of the vehicle, so as to calculate one or more output values.

As illustrated in FIG. **4**, the main computation section **1110** includes a first input matrix computation section **1111**, a second input matrix computation section **1112**, a third input matrix computation section **1113**, a fourth input matrix computation section **1118**, an adder **1114**, an integrator **1115**, a system matrix computation section **1116**, and an observation matrix computation section **1117**. Note that the first input matrix computation section **1111**, the second input matrix computation section **1112**, the third input matrix computation section **1113**, and the fourth input matrix computation section **1118** may be referred to as a first computation section.

To the first input matrix computation section **1111**, which carries out computation regarding an input matrix B**0** with respect to a ground surface input, road surface displacements (vertical displacements) z_{0fl}, z_{0fr}, z_{0rl}, and z_{0rr} are inputted, for example. Note that the subscripts "fl", "fr", "rl", and "rr" indicate that the road surface displacement is related to the left front wheel, the right front wheel, the left rear wheel, and the right rear wheel, respectively. Hereinafter, z_{0fl}, z_{0fr}, z_{0rl}, and z_{0rr} may be collectively indicated as z_{0fl} through z_{0rr}. The same also applies to other parameters.

The first input matrix computation section **1111** carries out computation using the input matrix B**0** with respect to the road surface displacements z_{0fl} through z_{0rr} inputted, and supplies a result of the computation thus carried out to the adder **1114**.

The second input matrix computation section **1112**, which carries out computation regarding an input matrix B**1** with respect to an operation amount, carries out computation using the input matrix B**1**, for example, with respect to a steering angle of the steering member **410** and supplies a result of the computation thus carried out to the adder **1114**.

The third input matrix computation section **1113**, which carries out computation regarding an input matrix B**2** with respect to a tire front and rear force and a tire lateral force, carries out computation using the input matrix B**2**, with respect to tire front and rear forces F_{x0fl} through F_{x0rr} of the respective wheels and tire lateral forces F_{y0fl} through F_{y0rr} of the respective wheels, the tire front and rear forces F_{x0fl} through F_{x0rr} and the tire lateral forces F_{y0fl} through F_{y0rr} being supplied from the tire model computation section **1140** (described later). The third input matrix computation section **1113** supplies a result of the computation thus carried out to the adder **1114**.

The fourth input matrix computation section **1118**, which carries out computation regarding an input matrix B**3** with respect to a force caused by a variable dumper or an active suspension, carries out computation using the input matrix B**3**, with respect to a reference output outputted from a steering stability and ride comfort control section **1150** (described later) and supplies a result of the computation thus carried out to the adder **1114**.

The adder **1114** adds respective outputs from the first input matrix computation section **1111**, the second input matrix computation section **1112**, the third input matrix computation section **1113**, the fourth input matrix computation section **1118**, and the system matrix computation section **1116** (described later) and supplies a result of addition thus carried out to the integrator **1115**.

The integrator **1115** integrates the result of the addition supplied from the adder **1114**. A result of integration thus carried out by the integrator **1115** is supplied to the third amplifier **1023** described above, the system matrix computation section **1116**, and the observation matrix computation section **1117**.

The system matrix computation section (second computation section) **1116** carries out computation using a system matrix A with respect to the result of the integration carried out by the integrator **1115** and supplies a result of the computation thus carried out to the adder **1114**.

The observation matrix computation section (third computation section) **1117** carries out computation using an observation matrix C with respect to the result of the integration carried out by the integrator **1115** and supplies a result of the computation thus carried out to the above-described subtractor **1012** as the reference output. The result of the computation carried out with use of the observation matrix C is also supplied to the slipping calculation section **1130**.

Note that the computation carried out by each section of the main computation section **1110** is carried out as linear computation. Accordingly, the main computation section **1110** having the configuration above makes it possible to suitably carry out linear computation with respect to a state amount related to a state of the vehicle with reference to one or more input values.

Further, an input to the main computation section **1110** is not limited to the above-described examples. For example, it is possible to employ a configuration in which at least one of:

steering torque;

wheel angular speed of each wheel;

actual rudder angle of each wheel; and

driving torque of each wheel

is inputted to the main computation section **1110** and the main computation section **1110** carries out linear computation with respect to an input value(s) of the at least one of these inputs. In such a case, for example, the main computation section **1110** may include a vehicle model switching section that switches between vehicle models respectively represented by the system matrix A, the input matrix B, and the observation matrix C, and the vehicle model switching section may switch between the vehicle models with reference to the above input(s).

It is also possible to employ a configuration in which the vehicle **900** includes a load detection sensor and a value detected by the load detection sensor is inputted to the main computation section **1110**. In such a case, for example, the main computation section **1110** may include a vehicle model switching section that switches between vehicle models respectively represented by the system matrix A, the input matrix B, and the observation matrix C depending on each load, and the vehicle model switching section may switch between the vehicle models in accordance with the value detected by the load detection sensor. Further, with use of a vehicle model before loading of the vehicle as a reference vehicle model, the sections **1300** of the vehicle may be controlled so that, in circumstances such as when the vehicle moves forward, turns, or is braked, the way in which the vehicle responded before the loading is resumed.

The input(s) to the main computation section **1110** may further include at least one of:

yaw rate;
front and rear G;
lateral G;
braking pressure;
VSA flag, TCS flag, and ABS flag;
engine torque; and
engine RPM.

In such a case, for example, the main computation section **1110** may include a vehicle model switching section that switches between vehicle models represented by the system matrix A, the input matrix B, and the observation matrix C, respectively, and the vehicle model switching section may switch between the vehicle models with reference to the above input(s). Further, with use of a reference vehicle model that allows the behavior and attitude of the vehicle under each running condition to be ideal, the sections **1300** of the vehicle may be controlled so that, in circumstances such as when the vehicle moves forward, turns, or is braked, the behavior and attitude of the vehicle are made ideal.

Example of State Amount which is Subject of Computation by Main Computation Section

The state amount which is a subject of computation by the main computation section **1110** is, for example, represented as follows as a state amount vector x. Note that a time derivative of the state amount below may also serve as a state amount that is a subject of computation by the main computation section **1110**.

$$x=[u,v,w,p,q,r,\varphi,\theta,\psi,\mathrm{DampSt}_{fl},\mathrm{DampSt}_{fr},\mathrm{DampSt}_{rl},\mathrm{DampSt}_{rr},z_{1flm},z_{1frm},z_{1rlm},z_{1rrm},w_{1flm},w_{1frm},w_{1rlm},w_{1rrm},\delta d\delta]r \quad \text{[Math. 1]}$$

where:

u, v, and w are respectively x-, y-, and z-direction components of a sprung speed of the vehicle body **200**; and

p, q, and r are respectively x-, y-, and z-direction components of a sprung angular speed of the vehicle body **200**, that is, a roll rate, a pitch rate, and a yaw rate. Further,

$$\varphi,\theta,\psi \quad \text{[Math. 2]}$$

are respectively the three components of Euler angles and may be written as phi, theta, and psi, respectively.

DampSt_{fl} through DampSt_{rr} are damper strokes of the respective wheels;

z_{1flm} through z_{1rrm} are unsprung displacements (displacements of unsprung portions) of the respective wheels;

w_{1flm} through w_{1rrm} are unsprung speeds (speeds of unsprung portions) of the respective wheels;

δ is an actual rudder angle; and

dδ is an actual rudder angle speed.

Note here that an x-direction indicates a traveling direction (front and rear direction) of the vehicle **900**, a z-direction indicates a vertical direction and a y-direction indicates a direction (lateral direction) perpendicular to both the x-direction and the z-direction.

Note that the actual rudder angle δ and the actual rudder angle speed dδ may be set individually for each wheel **300**.

Example of State Amount Outputted from Main Computation Section

A type of the reference output outputted from the main computation section **1110** is determined depending on how the observation matrix C is selected. For example, in a case where the reference output outputted from the main computation section **1110** is represented as a specific state amount vector y, the specific state amount vector y includes sprung vertical speed w, roll rate p, and pitch rate q as shown below.

$$y=[w,q,p,\mathrm{etc}]^T \quad \text{[Math. 3]}$$

Further, the reference output may include a damper stroke or a damper stroke speed of each wheel.

Thus, the reference output outputted from the main computation section **1110** is a physical quantity that can be represented with use of one or a combination of the state amounts included in the above-described state amount vector x.

Example of Motion Equation which is Subject of Computation by Main Computation Section

A motion equation which is a subject of computation by the main computation section **1110** is, for example, as follows.

Motion equations related to sprung translational and rotational motions:

$$F_x=m\dot{u}+m(qw-rv) \quad M_x=I_x\dot{p}-I_{xx}\dot{r}-(I_y-I_z)qr-I_{xx}pq$$

$$F_y=m\dot{v}+m(ru-pw) \quad M_y=I_y\dot{q}-(I_z-I_x)rp-I_{xx}(r^2-p^2)$$

$$F_z=m\dot{w}+m(pv-qu) \quad M_z=I_z\dot{r}-I_{xx}\dot{p}-(I_x-I_y)pq+I_{zz}qr \quad \text{[Math. 4]}$$

Motion equations related to Euler angles:

$$\dot{\varphi}=p+q\tan\theta\sin\varphi+r\tan\theta\cos\varphi$$

$$\dot{\theta}=q\cos\varphi-r\sin\varphi$$

$$\dot{\psi}=r\cos\varphi/\cos\theta+q\sin\varphi/\cos\theta \quad \text{[Math. 5]}$$

Motion equations related to unsprung vertical motion:

$$m_1\dot{w}_{1flm}=-F_{zflm}-k_{1f}(z_{1flm}-z_{0fl})$$

$$m_1\dot{w}_{1rlm}=-F_{xrlm}-k_{1r}(z_{1rlm}-z_{0rl})$$

$$m_1\dot{w}_{1frm}=-F_{xfrm}-k_{1f}(z_{1frm}-z_{0fr})$$

$$m_1\dot{w}_{1rrm}=-F_{xrrm}-k_{1r}(z_{1rrm}-z_{0rr}) \quad \text{[Math. 6]}$$

Motion equation related to actual rudder:

$$d\delta=\frac{1}{I_s}(-C_s d\delta-K_S(\delta-\alpha)) \quad \text{[Math. 7]}$$

In the motion equations above, m is a sprung mass of the vehicle (i.e., a mass of the vehicle body **200**),

F_x, F_y, and F_z are respectively x-, y-, and z-direction forces exerted on a sprung portion of the vehicle (i.e., on the vehicle body **200**),

M_x, M_y, and M_z are respectively x-, y-, and z-axial moments exerted on the sprung portion of the vehicle,

l_x, l_y, and l_z are respectively x-, y-, and z-axial inertia moments exerted on the sprung portion of the vehicle, and

l_{zx} is a product of inertia of the y-axis.

Further, F_{zflm} etc. are suspension forces of the respective wheels, and

m_1 is an unsprung mass. Further, the dot "•" written above each physical quantity represents a time derivative.

Further, α is a steering angle,

I_s is a wheel inertia moment about an axis of a kingpin,

C_s is an equivalent viscous friction coefficient of the kingpin, and

K_s is an equivalent elastic coefficient about the axis of the kingpin.

Apart from the above motion equations, a motion equation related to a rotational motion of a wheel is also a subject of computation carried out by the main computation section **1110**. Further, there are a plurality of relational expressions (e.g., relational expressions that relate a physical quantity of a sprung portion and a physical quantity of an upsprung portion to each other) that relate physical quantities present in those motion equations to each other. The motion equations are solved along with these relational expressions.

Linearization of Motion Equations and Implementation to Main Computation Section

The above-described motion equations are, in general, nonlinear and can be expressed as follows.

$$\dot{x}=f(x)+g(x)U \qquad \text{[Math. 8]}$$

where x is a vector indicative of a state amount, and f(x) and g(x) are functions of x and can be expressed as vectors.

In a case where a Taylor expansion of the above nonlinear motion equation is obtained and an initial value of each state amount is substituted into a Jacobian matrix, a matrix A as shown below is yielded. Matrices B and C as shown below are yielded in a similar fashion.

Consequently, linearized motion equations are expressed in a state space as follows.

$$\dot{x}=Ax+Bu$$

$$y=Cx \qquad \text{[Math. 9]}$$

where the matrix A corresponds to the above-described system matrix A, the matrix B corresponds to the above-described input matrices B**0**, B**1**, B**2**, and B**3**, and the matrix C corresponds to the above-described observation matrix C. Note that, as described later, the system matrix A has a matrix component that indicates a non-zero relationship between at least one of one or more state amounts in a planar direction and at least one of one or more of state amounts in an up-down direction.

It is thus shown from the above description that the main computation section **1110** illustrated in FIG. **4** is configured to linearly compute a motion equation that is a subject of computation.

Other Configurations of Reference Vehicle Model Computation Section

The following description will discuss configurations of the reference vehicle model computation section **1100** other than the main computation section **1110**.

The slipping calculation section **1130**, with reference to a result of computation carried out by the observation matrix computation section **1117** and wheel angular speeds ω_{fl} through ω_{rr} of the respective wheels detected by the wheel speed sensors **320**, calculates slip ratios s_{fl} through s_{rr} of the respective wheels and calculates, as a result of computation carried out by the observation matrix computation section **1117**, slip angles β_{fl} through β_{rr} of the respective wheels. The slipping calculation section **1130** supplies results of calculations thus carried out to the tire model computation section **1140**.

The tire grounding load calculation section **1120** calculates grounding loads F_{z0fl} through F_{z0rr} of the respective wheels on the basis of the unsprung displacements z_{1flm} through z_{1frrm} of the respective wheels obtained through the computation by the integrator **1115** and the road surface displacements z_{0fl} through z_{0rr} of the respective wheels, and supplies a result of calculation thus carried out to the tire model computation section **1140**.

The tire model computation section **1140** carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1110**. In the example illustrated in FIG. **4**, the tire model computation section **1140** carries out the nonlinear computation with reference to the slip ratios s_{fl} through s_{rr} of the respective wheels obtained from the computation carried out by the observation matrix computation section **1117**, the slip angles β_{fl} through β_{rr} of the respective wheels, and the grounding loads F_{z0fl} through F_{z0rr} of the respective wheels computed by the tire grounding load calculation section **1120**. That is, in the example illustrated in FIG. **4**, the tire model computation section **1140** carries out the nonlinear computation with indirect reference to at least part of a result of computation carried out by the main computation section **1110**.

More specifically, the tire model computation section **1140** calculates the tire front and rear forces F_{x0fl} through F_{x0rr} of the respective wheels and the tire lateral forces F_{y0fl} through F_{y0rr} of the respective wheels, with use of an arithmetic expression related to a tire model and with reference to the slip ratios s_{fl} through s_{rr} of the respective wheels, the slip angles β_{fl} through β_{rr} of the respective wheels, and the grounding loads F_{z0fl} through F_{z0rr} of the respective wheels. A specific example of the arithmetic expression used by the tire model computation section **1140** may be

$$F_{Px0fl}=D_{xfl}\cdot\sin[C_{xfl}\cdot\tan^{-1}\{B_{xfl}\cdot s_{xfl}-E_{xfl}(B_{xfl}\cdot s_{xfl}-\tan^{-1}(B_{xfl}\cdot s_{xfl}))\}]+S_{vxfl}$$

$$F_{Py0fl}=D_{yfl}\cdot\sin[C_{yfl}\cdot\tan^{-1}\{B_{yfl}\cdot\beta_{yfl}-E_{yfl}(B_{yfl}\cdot\beta_{yfl}-\tan^{-1}(B_{yfl}\cdot\beta_{yfl}))\}]+S_{vyfl}$$

$$F_{x0fl}=F_{Px0fl}\cdot G_{x\beta fl}$$

$$F_{y0fl}=F_{Py0fl}\cdot G_{x\beta fl}+S_{vyxfl}$$

$$s_{xfl}=s_{fl}+S_{Hxfl}$$

$$\beta_{yfl}=\beta_{fl}+S_{Hyfl} \qquad \text{[Math. 10]}$$

but Embodiment 1 is not limited to these. Note that in a first expression, F_{Px0f1} indicates a tire front and rear force of the left front wheel in a case where the vehicle is moving straight forward. Each variable is a value that depends on a characteristic of the tire and/or on F_{z0fl}. In a second expression, F_{Py0fl} indicates a tire lateral force in a case where no tire front and rear force is involved.

Note that the tire model computation section **1140**, which carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1110**, may be regarded as a tire force estimation device that calculates the tire front and rear forces F_{x0fl} through F_{x0rr} of the respective wheels and the tire lateral forces F_{y0fl} through F_{y0rr} of the respective wheels.

As described above, in the reference vehicle model computation section **1100** in accordance with Embodiment 1, the main computation section **1110** carries out linear computation and the tire model computation section **1140** carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1110**. By thus employing a configuration in which a linear computation section and a nonlinear computation section are provided separately from each other, it is possible to suitably carry out computation with respect to a state amount with use of a vehicle model.

Further, since the tire model computation section **1140** carries out nonlinear computation based on a tire model, nonlinear computation can be suitably separated from linear computation.

Further, as described above, the third input matrix computation section **1113** takes in, as an input, a result of nonlinear computation carried out by the tire model computation section **1140**. This makes it possible to suitably take the result of the nonlinear computation into linear computation carried out by the main computation section **1110**. This allows the main computation section **1110** to achieve highly accurate computation while carrying out linear computation.

Inseparable Computation by Reference Vehicle Model Computation Section **1100**

The following description will discuss, with reference to another drawing, computation carried out by the reference vehicle model computation section **1100** with respect to a state amount in a planar direction and a state amount in an up-down direction in an inseparable manner. FIG. **5** is a table illustrating a specific example of components of the system matrix A which is used in computation carried out by the system matrix computation section **1116** of the reference vehicle model computation section **1100** with respect to a result of integration carried out by the integrator **1115**. Note that $DampSt_{fl}$, $DampSt_{fr}$, $DampSt_{rl}$, $DampSt_{rr}$, z_{1flm}, z_{1frm}, z_{1rlm}, z_{1rrm}, w_{1flm}, w_{1frm}, w_{1rlm}, and w_{1rrm} written herein are indicated as DampStfl, DampStfr, DampStrl, DampStrr, z1flm, z1frm, z1rlm, z1rrm, w1flm, w1frm, w1rlm, and w1rrm, respectively, in the table of FIG. **5**.

In the table of FIG. **5**, (i) u, v, r, psi, w, p, q, phi, theta, $DampSt_{fl}$ through $DampSt_{rr}$, z_{1flm} through z_{1rrm}, and w_{1flm} through w_{1rrm}, which indicate columns of the table, are above-described state amounts related to the vehicle **900**, and (ii) deltaf and deltaVf, which also indicate columns of the table, are actual rudder angle and actual rudder angle speed, respectively.

Further, as illustrated in FIG. **5**, u through deltaVf are state amounts related to a planar motion of the vehicle, and w through w_{1rrm} are state amounts related to the up-down direction of the vehicle.

State amounts that indicate rows of the table of FIG. **5** represent respective time derivatives of the above state amounts that indicate columns. As illustrated in FIG. **5**, a corresponding state amount is expressed with use of a letter "d" which means time derivative.

Further, as illustrated in FIG. **5**, du through deltaVf are time derivatives of state amounts related to a planar motion of the vehicle, and dw through dw_{1rrm} are time derivatives of state amounts related to the up-down direction of the vehicle.

As is clear from FIG. **5**, the matrix A used by the system matrix computation section **1116** for computation has a matrix component that indicates a non-zero relationship between at least one of one or more state amounts in the planar direction and at least one of one or more state amounts in the up-down direction.

For example, as illustrated in FIG. **5**, the matrix A has a non-zero component in the "p" column of the "dr" row. This means that the system matrix computation section **1116** carries out computation with respect to a roll rate "p", which is a state amount in the up-down direction, and a time derivative "dr" of yaw rate, which is a state amount in the planar direction, in a coupled manner. In other words, the system matrix computation section **1116** carries out computation with respect to a state amount in the planar direction and a state amount in the up-down direction in an inseparable manner. Note that "computation in a coupled manner" encompasses computation in which one state amount that is a subject of the computation is expressed by another state amount that is a subject of the computation. For example, in the case of the example above, the time derivative "dr" of yaw rate is expressed by the roll rate "p".

Thus, the ECU **600** includes the reference vehicle model computation section **1100** which is a suspension control device configured to control a suspension to follow a reference vehicle model and carries out computation with use of the reference vehicle model. Further, since the reference vehicle model computation section **1100** calculates a reference output by carrying out computation with respect to at least one of a plurality of state amounts in the planar direction and at least one of a plurality of state amounts in the up-down direction in an inseparable manner, it is possible to suitably express a vehicle behavior in which the state amounts are coupled. Therefore, the above configuration improves accuracy in estimation of a state of the vehicle. Accordingly, the above configuration allows providing enhanced ride comfort to a driver.

Further, since the matrix A used by the system matrix computation section **1116** for computation has a matrix component that indicates a non-zero relationship between at least one of one or more state amounts in the planar direction and at least one of one or more state amounts in the up-down direction, computation with respect to at least one of the one or more state amounts in the planar direction and at least one of the one or more state amounts in the up-down direction can be carried out by matrix computation suitably in an inseparable manner.

Vehicle State Estimation Section

The following description will discuss details of the vehicle state estimation section **1200** with reference to another drawing.

The vehicle state estimation section **1200** carries out computation with respect to an input value with use of a vehicle model for estimation and supplies an estimation output, which is a result of the computation, to the subtractor **1012**. Further, the vehicle state estimation section **1200** supplies various state amounts that are subjects of the computation to the first amplifier **1021**. The estimation output outputted from the vehicle state estimation section **1200** serves as an estimated value of each physical quantity related to the vehicle.

FIG. **6** is a block diagram illustrating an example of a configuration of the vehicle state estimation section **1200**. As illustrated in FIG. **6**, the vehicle state estimation section **1200** includes a main computation section **1210**, a tire grounding load calculation section **1220**, a slipping calculation section **1230**, and a tire model computation section **1240**.

Main Computation Section

The main computation section **1210** refers to one or more input values and carries out linear computation for a state amount related to a state of the vehicle, so as to calculate one or more output values.

As illustrated in FIG. **6**, the main computation section **1210** includes a first input matrix computation section **1211**, a second input matrix computation section **1212**, a third input matrix computation section **1213**, a fifth input matrix computation section **1219**, an adder **1214**, an integrator **1215**, a system matrix computation section **1216**, and an observation matrix computation section **1217**. Note that the first input matrix computation section **1211**, the second input matrix computation section **1212**, the third input matrix computation section **1213**, and the fifth input matrix computation section **1219** may be referred to as a first computation section.

To the first input matrix computation section **1211**, which carries out computation regarding an input matrix B**0'** with respect to a ground surface input, road surface displacements (vertical displacements) z_{0fl}, z_{0fr}, z_{0rl}, and z_{0rr} are inputted, for example.

The first input matrix computation section **1211** carries out computation using the input matrix B**0'** with respect to the road surface displacements z_{0fl} through z_{0rr} inputted, and supplies a result of the computation thus carried out to the adder **1214**. Note that the input matrix B**0'** used in the computation carried out by the first input matrix computation section **1211** may be the same as or different from the input matrix B**0** used in the computation carried out by the first input matrix computation section **1111**.

The second input matrix computation section **1212**, which carries out computation regarding an input matrix B**1'** with respect to an operation amount, carries out computation using the input matrix B**1'**, for example, with respect to a steering angle of the steering member **410** and supplies a result of the computation thus carried out to the adder **1214**. Note that the input matrix B**1'** used in the computation carried out by the second input matrix computation section **1212** may be the same as or different from the input matrix B**1** used in the computation carried out by the second input matrix computation section **1112**.

The third input matrix computation section **1213**, which carries out computation regarding an input matrix B**2'** with respect to a tire front and rear force and a tire lateral force, carries out computation using the input matrix B**2'**, for example, with respect to tire front and rear forces F_{x0fl} through F_{x0rr} of the respective wheels and tire lateral forces F_{y0fl} through F_{y0rr} of the respective wheels, the tire front and rear forces F_{x0fl} through F_{x0rr} and the tire lateral forces F_{y0fl} through F_{y0rr} being supplied from the tire model computation section **1240** (described later). The third input matrix computation section **1213** supplies a result of the computation thus carried out to the adder **1214**. Note that the input matrix B**2'** used in the computation carried out by the third input matrix computation section **1213** may be the same as or different from the input matrix B**2** used in the computation carried out by the third input matrix computation section **1113**.

To the fifth input matrix computation section **1219**, which carries out computation regarding an input matrix B**4** with respect to an output from the control amount computation section **1000**, an output from the control amount computation section **1000** is inputted. The fifth input matrix computation section **1219** carries out computation using the input matrix B**4** with respect to the output from the control amount computation section **1000** and supplies a result of the computation thus carried out to the adder **1214**.

The adder **1214** adds respective outputs from the first input matrix computation section **1211**, the second input matrix computation section **1212**, the third input matrix computation section **1213**, the fifth input matrix computation section **1219**, and the system matrix computation section **1216** (described later) and supplies a result of addition thus carried out to the integrator **1215**.

The integrator **1215** integrates the result of the addition supplied from the adder **1214**. A result of integration thus carried out by the integrator **1215** is outputted as an estimation state amount and supplied to the system matrix computation section **1216** and the observation matrix computation section **1217**.

The system matrix computation section (second computation section) **1216** carries out computation using a system matrix A' with respect to the result of the integration carried out by the integrator **1215** and supplies a result of the computation thus carried out to the adder **1214**. Note that the system matrix A' may be the same as or different from the system matrix A used in the computation carried out by the system matrix computation section **1116**.

The observation matrix computation section (third computation section) **1217** carries out computation using an observation matrix C' with respect to the result of the integration carried out by the integrator **1215** and supplies a result of the computation thus carried out to the above-described subtractor **1012** as the estimation output. The result of the computation carried out with use of the observation matrix C' is also supplied to the slipping calculation section **1230**. Note that the observation matrix C' may be the same as or different from the observation matrix C used in the computation carried out by the observation matrix computation section **1117**.

Note that the computation carried out by each section of the main computation section **1210** is carried out as linear computation. Accordingly, the main computation section **1210** having the configuration above makes it possible to suitably carry out linear computation with respect to a state amount related to a state of the vehicle with reference to one or more input values.

Further, as with the main computation section **1110**, an input to the main computation section **1210** is not limited to the above-described examples. For example, it is possible to employ a configuration in which at least one of:

steering torque;

wheel angular speed of each wheel;

actual rudder angle of each wheel; and

driving torque of each wheel

is inputted to the main computation section **1210** and the main computation section **1210** carries out linear computation with respect to an input value(s) of the at least one of these inputs. In such a case, for example, the main computation section **1210** may include a vehicle model switching section that switches between vehicle models represented by the system matrix A', the input matrix B', and the observation matrix C', respectively, and the vehicle model switching section may switch between the vehicle models with reference to the above input(s).

It is also possible to employ a configuration in which the vehicle **900** includes a load detection sensor and a value detected by the load detection sensor is inputted to the main computation section **1210**. In such a case, for example, the main computation section **1210** may include a vehicle model switching section that switches between vehicle models respectively represented by the system matrix A', the input matrix B', and the observation matrix C' depending on each load, and the vehicle model switching section may switch between the vehicle models in accordance with the value detected by the load detection sensor.

The input(s) to the main computation section **1210** may further include at least one of:

yaw rate;
front and rear G;
lateral G;
braking pressure;
VSA flag, TCS flag, and ABS flag;
engine torque; and
engine RPM.

In such a case, for example, the main computation section **1210** may include a vehicle model switching section that switches between vehicle models represented by the system matrix A', the input matrix B', and the observation matrix C', respectively, and the vehicle model switching section may switch between the vehicle models with reference to the above input(s).

Example of State Amount which is Subject of Computation by Main Computation Section

A state amount that is a subject of computation carried out by the main computation section **1210** is similar to a state amount that is a subject of computation carried out by the main computation section **1110**, and will not be discussed in detail herein. Note that the reference output outputted from the main computation section **1210** is a physical quantity that can be represented with use of one or a combination of the state amounts included in the above-described state amount vector x, as with the case of the main computation section **1110**.

Example of State Amount Outputted from Main Computation Section

A type of the estimation output outputted from the main computation section **1210** is determined depending on how the observation matrix C is selected. For example, as with the reference output outputted from the main computation section **1110**, the estimation output outputted from the main computation section **1110** includes sprung vertical speed w, roll rate p, and pitch rate q.

Further, the reference output may include a damper stroke or a damper stroke speed of each wheel.

Thus, the estimation output outputted from the main computation section **1210** is a physical quantity that can be represented with use of one or a combination of the state amounts included in the above-described state amount vector x.

Linearization of Motion Equations and Implementation to Main Computation Section

Linearization of motion equations and implementation of the motion equations to the main computation section **1210** are similar to those discussed in the descriptions of implementation to the main computation section **1110**, and will not be discussed in detail herein. Note that the matrices A and C in the linearized motion equations discussed in the descriptions of implementation to the main computation section **1110** correspond to the matrices A' and C' in the main computation section **1210**, and the matrix B in the linearized motion equation corresponds to the matrices B**0**', B**1**', B**2**', and B**4** in the main computation section **1210**.

It is thus shown from the above description that the main computation section **1210** illustrated in FIG. **6** is configured to linearly compute a motion equation that is a subject of computation.

Other Configurations of Vehicle State Estimation Section

The following description will discuss configurations of the vehicle state estimation section **1200** other than the main computation section **1210**.

The slipping calculation section **1230**, with reference to a result of computation carried out by the observation matrix computation section **1217** and wheel angular speeds con through co, of the respective wheels detected by the wheel speed sensors **320**, calculates slip ratios s_{fl} through s_{rr} of the respective wheels and calculates, as a result of computation carried out by the observation matrix computation section **1217**, slip angles β_{fl} through β_{rr} of the respective wheels. The slipping calculation section **1230** supplies results of calculations thus carried out to the tire model computation section **1140**.

The tire grounding load calculation section **1220** calculates grounding loads F_{z0fl} through F_{z0rr} of the respective wheels on the basis of the unsprung displacements z_{1flm} through z_{1frrm} of the respective wheels obtained through the computation by the integrator **1215** and the road surface displacements z_{0fl} through z_{0rr} of the respective wheels, and supplies a result of calculation thus carried out to the tire model computation section **1240**.

The tire model computation section **1240** carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1210**. In the example illustrated in FIG. **6**, the tire model computation section **1240** carries out the nonlinear computation with reference to the slip ratios s_{fl} through s_{rr} of the respective wheels obtained from the computation carried out by the observation matrix computation section **1217**, the slip angles β_{fl} through β_{rr} of the respective wheels obtained from the computation carried out by the observation matrix computation section **1217**, and the grounding loads F_{z0fl} through F_{z0rr} of the respective wheels computed by the tire grounding load calculation section **1220**. That is, in the example illustrated in FIG. **6**, the tire model computation section **1240** carries out the nonlinear computation with indirect reference to at least part of a result of computation carried out by the main computation section **1210**.

Details of a computation process carried out by the tire model computation section **1240** are similar to those of the tire model computation section **1140**, and will not be discussed in detail herein.

Note that the tire model computation section **1240**, which carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1210**, may be regarded as a tire force estimation device that calculates the tire front and rear forces F_{x0fl} through F_{x0rr} of the respective wheels and the tire lateral forces F_{y0fl} through F_{x0rr} of the respective wheels.

As described above, in the vehicle state estimation section **1200** in accordance with Embodiment 1, the main computation section **1210** carries out linear computation and the tire model computation section **1240** carries out nonlinear computation with direct or indirect reference to at least part of a result of computation carried out by the main computation section **1210**. By thus employing a configuration in which a linear computation section and a nonlinear computation section are provided separately from each other, it is possible to suitably carry out computation with respect to a state amount with use of a vehicle model.

Further, since the tire model computation section **1240** carries out nonlinear computation based on a tire model, nonlinear computation can be suitably separated from linear computation.

Further, as described above, the third input matrix computation section **1213** takes in, as an input, a result of nonlinear computation carried out by the tire model computation section **1240**. This makes it possible to suitably take the result of the nonlinear computation into linear computation carried out by the main computation section **1210**. This allows the main computation section **1210** to achieve highly accurate computation while carrying out linear computation.

Steering Stability and Ride Comfort Control Section **1150**

The steering stability and ride comfort control section **1150** determines a control amount for controlling each section of a reference vehicle model and influences, in order to supply the control amount to the sections, the reference output outputted from the observation matrix computation section **1117**. An output from the steering stability and ride comfort control section **1150** is supplied to the fourth input matrix computation section **1118**, and computation is carried out with use of the input matrix B**3**.

For example, the steering stability and ride comfort control section **1150** carries out (i) processes of skyhook control, roll attitude control, pitch attitude control, and unsprung portion control and (ii) a process of selecting a control amount.

Note that the skyhook control means a ride comfort control (damping control) for improving ride comfort by suppressing oscillation of the reference vehicle model caused at the time of driving over irregular road surfaces.

In the skyhook control, a skyhook target control amount is determined, for example, with reference to a sprung speed of a reference vehicle model, a four-wheel stroke speed, a pitch rate, and a roll rate, and a result thus determined is regarded as a subject of the process of selecting a control amount.

In the roll attitude control, target control amounts are calculated with reference to a roll rate during steering and a rudder angle, and a result of calculation thus carried out is regarded as a subject of the process of selecting a control amount.

In the pitch attitude control, pitch control is carried out with reference to a pitch rate during acceleration so as to calculate a pitch target control amount, and a result of calculation thus carried out is regarded as a subject of the process of selecting a control amount.

In the unsprung portion control, damping control of an unsprung portion of the vehicle is carried out with reference to a four-wheel wheel speed so as to determine an unsprung-portion-damping target control amount, and a result thus determined is used as a subject of the process of selecting a control amount.

In the process of selecting a control amount, a target control amount having the highest value may be selected and outputted from among the skyhook target control amount, the target control amounts calculated in the roll attitude control, the pitch target control amount, and the unsprung-portion-damping target control amount.

Embodiment 2

Embodiment 1 above discussed an example configuration in which computation related to a tire model is carried out by the tire model computation section **1140** nonlinearly. Note, however, that the invention disclosed herein is not limited to this configuration.

Embodiment 2 will discuss a configuration in which computation related to a tire model is also linearized. FIG. **7** is a block diagram illustrating a configuration of a reference vehicle model computation section **1100***a* in accordance with Embodiment 2. An ECU **600** in accordance with Embodiment 2 includes a reference vehicle model computation section **1100***a* in place of the reference vehicle model computation section **1100** described in Embodiment 1. Note that similar configurations as those of Embodiment 1 will not be discussed below. Further, a vehicle state estimation section **1200***a* in accordance with Embodiment 2 can be configured similarly as the reference vehicle model computation section **1100***a*. Description of the vehicle state estimation section **1200***a* will not be given below since it will be clear from the following description of the reference vehicle model computation section **1100***a*.

As illustrated in FIG. **7**, the reference vehicle model computation section **1100***a* does not include the tire grounding load calculation section **1120**, the slipping calculation section **1130**, and the tire model computation section **1140** which are included in the reference vehicle model computation section **1100**.

In the reference vehicle model computation section **1100***a*, a contribution related to a tire model is included in matrix components of a matrix A. Accordingly, computation carried out by the reference vehicle model computation section **1100***a* reflects a linearized tire model characteristic.

Inseparable Computation by Reference Vehicle Model Computation Section **1100***a*

As with Embodiment 1, the reference vehicle model computation section **1100***a* in accordance with Embodiment 2 carries out computation with respect to a state amount in a planar direction and a state amount in an up-down direction in an inseparable manner.

FIG. **8** is a table illustrating a specific example of components of a system matrix A which is used in computation carried out by a system matrix computation section **1116** of the reference vehicle model computation section **1100***a* with respect to a result of integration carried out by an integrator **1115**. Note that $DampSt_{fl}$, $DampSt_{fr}$, $DampSt_{rl}$, $DampSt_{rr}$, z_{1flm}, z_{1frm}, z_{1rlm}, z_{1rrm}, w_{1flm}, w_{1frm}, w_{1rlm}, and w_{1rrm} written herein are indicated as DampStfl, DampStfr, DampStrl, DampStrr, z1flm, z1frm, z1rlm, z1rrm, w1flm, w1frm, w1rlm, and w1rrm, respectively, in the table of FIG. **8**.

As illustrated in FIG. **8**, the matrix A used by the system matrix computation section **1116** for computation has a matrix component that indicates a non-zero relationship between at least one of one or more state amounts in the planar direction and at least one of one or more state amounts in the up-down direction.

For example, as illustrated in FIG. **8**, the matrix A has a non-zero component in the "q" column of the "du" row. This means that the system matrix computation section **1116** carries out computation with respect to a time derivative of a sprung speed "u", which is a state amount in the planar direction, and a pitch rate "q", which is a state amount in the up-down direction, in a coupled manner. In other words, the system matrix computation section **1116** carries out computation with respect to a state amount in the planar direction and a state amount in the up-down direction in an inseparable manner.

Thus, the reference vehicle model computation section **1100***a* carries out, in an inseparable manner, computation with respect to (i) a time derivative "du" or "dv" of a planar direction component of a sprung speed of the vehicle body as at least part of a plurality of state amounts in the planar direction and (ii) at least one of a roll rate "p" or a pitch rate "q" of the vehicle body as at least part of a plurality of state amounts in the up-down direction. This allows suitably expressing a behavior of the vehicle.

Further, the reference vehicle model computation section **1100***a* carries out, in an inseparable manner, computation with respect to (i) a planar direction component "u" or "v" of a sprung speed of the vehicle body as at least part of the plurality of state amounts in the planar direction and (ii) at least one of a time derivative "dp" of a roll rate and a time derivative "dq" of a pitch rate of the vehicle body as at least part of the plurality of state amounts in the up-down direction. This allows suitably expressing a behavior of the vehicle.

Further, the reference vehicle model computation section **1100***a* carries out, in an inseparable manner, computation with respect to (i) a time derivative "dr" of a yaw rate of the vehicle body as at least part of the plurality of state amounts in the planar direction and (ii) a damper stroke (one of DampStfl through DampStrr) of at least one of the wheels as at least part of the plurality of state amounts in the up-down direction. This allows suitably expressing a behavior of the vehicle.

Thus, since the reference vehicle model computation section **1100***a* carries out computation with respect to at least one of a plurality of state amounts in the planar direction and at least one of a plurality of state amounts in the up-down direction in an inseparable manner, it is possible to suitably express a vehicle behavior. Accordingly, the above configuration allows providing enhanced ride comfort to a driver.

Supplementary Notes on Embodiments 1 and 2

Embodiments 1 and 2 above discussed example configurations in which the reference vehicle model computation section **1100** or the reference vehicle model computation section **1100***a* includes a linear computation section. Note, however, that the invention disclosed herein is not limited to these configurations. The reference vehicle model computation section **1100** or the reference vehicle model computation section **1100***a* may include a nonlinear computation section instead of the above-described linear computation section. In other words, the reference vehicle model computation section **1100** or the reference vehicle model computation section **1100***a* may consist solely of a nonlinear computation section. Motion equations including various state amounts and the like used in computation by the reference vehicle model computation section **1100** or the reference vehicle model computation section **1100***a* including a nonlinear computation section include a nonlinear term, i.e., a term of second or higher degree. This configuration also improves accuracy in estimation of a state of the vehicle, due to the fact that the reference vehicle model computation section **1100** or the reference vehicle model computation section **1100***a* carries out computation with respect to at least one of one or more state amounts in the planar direction and at least one of one or more state amounts in the up-down direction in an inseparable manner.

Software Implementation Example

Control blocks of the ECU **600** (particularly, the control amount computation section **1000** and the vehicle state estimation section **1200**) can be realized by a logic circuit (hardware) provided in an integrated circuit (IC chip) or the like or can be alternatively realized by software as executed by a central processing unit (CPU).

In the latter case, the ECU **600** includes a CPU that executes instructions of a program that is software realizing the foregoing functions; a read only memory (ROM) or a storage device (each referred to as "storage medium") in which the program and various kinds of data are stored so as to be readable by a computer (or a CPU); and a random access memory (RAM) in which the program is loaded. An object of the present invention can be achieved by a computer (or a CPU) reading and executing the program stored in the storage medium. Examples of the storage medium encompass "a non-transitory tangible medium" such as a tape, a disk, a card, a semiconductor memory, and a programmable logic circuit. The program can be made available to the computer via any transmission medium (such as a communication network or a broadcast wave) which allows the program to be transmitted. Note that the present invention can also be achieved in the form of a computer data signal in which the program is embodied via electronic transmission and which is embedded in a carrier wave.

The present invention is not limited to the embodiments, but can be altered by a skilled person in the art within the scope of the claims. The present invention also encompasses, in its technical scope, any embodiment derived by combining technical means disclosed in differing embodiments.

REFERENCE SIGNS LIST

100 suspension
200 vehicle body
600 ECU (suspension control device, suspension control section)
1000 control amount computation section
1012 subtractor
1014 integrator
1021 first amplifier
1022 second amplifier
1023 third amplifier
1024 adder
1100, **1100***a* reference vehicle model computation section
1110 main computation section
1111 first input matrix computation section (first computation section)
1112 second input matrix computation section (first computation section)
1113 third input matrix computation section (first computation section)
1114 adder
1115 integrator
1116 system matrix computation section (second computation section)
1117 observation matrix computation section (third computation section)
1140 tire model computation section
1200 vehicle state estimation section

The invention claimed is:

1. A suspension device, comprising:
a suspension;
a processor; and
a memory, wherein
the processor includes a suspension control section configured to control the suspension to follow a reference vehicle model,
the suspension control section including a reference vehicle model computation section which includes:
a main computation section which refers to one or more input values, carries out linear computation for a

state amount related to a state of the vehicle, and outputs a result of the linear computation; and

a slipping calculation section which refers to the result of the linear computation carried out by the main computation section and calculates respective slip angles of wheels,

the reference vehicle model computation section is configured to:

carry out computation with use of the reference vehicle model;

calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner; and,

carry out, in an inseparable manner, computation with respect to (i) a time derivative of a planar direction component of a sprung speed of a vehicle body as at least part of the plurality of state amounts in the planar direction and (ii) at least one of a roll rate and a pitch rate of the vehicle body as at least part of the plurality of state amounts in the up-down direction wherein:

the processor includes:

a vehicle state estimation configured to estimate the state of the vehicle;

a subtractor configured to carry out subtraction, from an estimation output amount which is an output from the vehicle state estimation section, of a specific state amount which is the output value outputted from the reference vehicle model computation section;

an integrator configured to carry out integration of a result of the subtraction carried out by the subtractor;

a first amplifier configured to carry out amplification of an estimation state amount which is a subject of computation carried out by the vehicle state estimation section;

a second amplifier configured to carry out amplification of a result of the integration carried out by the integrator;

a third amplifier configured to carry out amplification of the state amount which is a subject of computation carried out by the reference vehicle model computation section; and

an adder configured to carry out addition of a result of the amplification carried out by the first amplifier, a result of the amplification carried out by the second amplifier, and a result of the amplification carried out by the third amplifier,

the suspension control section being configured to determine a suspension control amount with reference to a result of the addition carried out by the adder to control the suspension, and

the one or more input values including at least one of a road surface displacement of each wheel, a steering angle of a steering member, tire front and rear force of each wheel, tire lateral force of each wheel, steering torque, a wheel angular speed of each wheel, an actual rudder angle of each wheel, and driving torque of each wheel.

2. A suspension device, comprising:

a suspension;

a processor; and

a memory, wherein

the processor includes a suspension control section configured to control the suspension to follow a reference vehicle model,

the suspension control section including a reference vehicle model computation section which includes:

a main computation section which refers to one or more input values, carries out linear computation for a state amount related to a state of the vehicle, and outputs a result of the linear computation; and

a slipping calculation section which refers to the result of the linear computation carried out by the main computation section and calculates respective slip angles of wheels,

the reference vehicle model computation section is configured to:

carry out computation with use of the reference vehicle model;

calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner; and,

carry out, in an inseparable manner, computation with respect to (i) a planar direction component of a sprung speed of a vehicle body as at least part of the plurality of state amounts in the planar direction and (ii) at least one of a time derivative of a roll rate and a time derivative of a pitch rate of the vehicle body as at least part of the plurality of state amounts in the up-down direction wherein:

the processor includes:

a vehicle state estimation configured to estimate the state of the vehicle;

a subtractor configured to carry out subtraction, from an estimation output amount which is an output from the vehicle state estimation section, of a specific state amount which is the output value outputted from the reference vehicle model computation section;

an integrator configured to carry out integration of a result of the subtraction carried out by the subtractor;

a first amplifier configured to carry out amplification of an estimation state amount which is a subject of computation carried out by the vehicle state estimation section;

a second amplifier configured to carry out amplification of a result of the integration carried out by the integrator;

a third amplifier configured to carry out amplification of the state amount which is a subject of computation carried out by the reference vehicle model computation section; and

an adder configured to carry out addition of a result of the amplification carried out by the first amplifier, a result of the amplification carried out by the second amplifier, and a result of the amplification carried out by the third amplifier,

the suspension control section being configured to determine a suspension control amount with reference to a result of the addition carried out by the adder to control the suspension, and

the one or more input values including at least one of a road surface displacement of each wheel, a steering angle of a steering member, tire front and rear force of each wheel, tire lateral force of each wheel, steering torque, a wheel angular speed of each wheel, an actual rudder angle of each wheel, and driving torque of each wheel.

3. A suspension device, comprising:

a suspension;

a processor; and

a memory, wherein

the processor includes a suspension control section configured to control the suspension to follow a reference vehicle model,

the suspension control section including a reference vehicle model computation section which includes:

a main computation section which refers to one or more input values, carries out linear computation for a state amount related to a state of the vehicle, and outputs a result of the linear computation; and

a slipping calculation section which refers to the result of the linear computation carried out by the main computation section and calculates respective slip angles of wheels,

the reference vehicle model computation section is configured to:

carry out computation with use of the reference vehicle model;

calculate a reference output by carrying out computation with respect to at least one of a plurality of state amounts in a planar direction and at least one of a plurality of state amounts in an up-down direction in an inseparable manner; and,

carry out, in an inseparable manner, computation with respect to (i) a time derivative of a yaw rate of a vehicle body as at least part of the plurality of state amounts in the planar direction and (ii) a damper stroke of at least one of wheels as at least part of the plurality of state amounts in the up-down direction wherein:

the processor includes:

a vehicle state estimation configured to estimate the state of the vehicle;

a subtractor configured to carry out subtraction, from an estimation output amount which is an output from the vehicle state estimation section, of a specific state amount which is the output value outputted from the reference vehicle model computation section;

an integrator configured to carry out integration of a result of the subtraction carried out by the subtractor;

a first amplifier configured to carry out amplification of an estimation state amount which is a subject of computation carried out by the vehicle state estimation section;

a second amplifier configured to carry out amplification of a result of the integration carried out by the integrator;

a third amplifier configured to carry out amplification of the state amount which is a subject of computation carried out by the reference vehicle model computation section; and

an adder configured to carry out addition of a result of the amplification carried out by the first amplifier, a result of the amplification carried out by the second amplifier, and a result of the amplification carried out by the third amplifier,

the suspension control section being configured to determine a suspension control amount with reference to a result of the addition carried out by the adder to control the suspension, and

the one or more input values including at least one of a road surface displacement of each wheel, a steering angle of a steering member, tire front and rear force of each wheel, tire lateral force of each wheel, steering torque, a wheel angular speed of each wheel, an actual rudder angle of each wheel, and driving torque of each wheel.

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